Engineering Geology 233 (2018) 172–182

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Geohazard cascade and mechanism of large debris flows in Tianmo gully, SE Tibetan Plateau and implications to hazard monitoring

Rongqiang Wei[a,b], Qingli Zeng[a,b,*], Tim Davies[c], Guangxiang Yuan[d], Kaiyang Wang[b,e], Xinyu Xue[b], Qianfeng Yin[b]

[a] Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing 100049, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Department of Geological Sciences, University of Canterbury, Christchurch 8041, New Zealand
[d] College of Resources and Environment, North China University of Water Resources and Electric Power, Zhengzhou 450045, China
[e] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

ARTICLE INFO

Keywords:
Rock avalanche
Landslide dam-breach
Geohazard cascade
Deglaciation
Sichuan-Tibet highway/railway

ABSTRACT

Alpine glaciers and permafrost are sensitive to climate change, and their degradation due to annual temperature increasing has already induced many mass movements such as debris flows. On September 4 of 2007, July 25–31 and September 5–8 of 2010, three large debris flows took place in Tianmo gully, a left-bank tributary of Parlung River, southeast Tibetan Plateau. The debris flows blocked the river, and a section of highway 450 m long including a bridge 76 m long were destroyed by the subsequent outburst flood. This paper, based on post-event investigations, witness accounts, news reports and satellite image interpretation, systematically analyses the geo-environments, climate conditions and sources of these debris flow events. Their differences in flow process, surge numbers and velocity suggest that they resulted from different geohazard processes, cascades and initiation mechanisms. The 2007 debris flow originated from a bare rock/moraine collapse next to the cirque due to strong alternation of wet and dry conditions. The mass moved down the gully with velocity of 30–40 m/s estimated by back-calculation using superelevation and run-up. It entrained moraine, avalanched snow-ice and water from the channel, and transformed into high-speed debris flow, crossing the Parlung River and finally depositing onto the highway. The other two events in July and September of 2010 initiated from two channel-bank landslides triggered by melt-water and concentrated rainfall, which dammed the channel. The subsequent landslide dam failure generated debris flows over several days, with velocities of 12–14 m/s, that temporally blocked Parlung River. The initiation mechanisms of most large debris flows recorded in Parlung region are similar to the events in Tianmo gully, originating either from rock/moraine avalanches or from the collapse of a landslide dam. This implies that the periglacial degradation of bedrock and moraine is the key process to be monitored and assessed under climate warming. The paper applies the geohazard mechanisms and cascade to hazard monitoring in order to protect the existing Sichuan-Tibet highway and the forthcoming railway.

1. Introduction

Debris flows comprise an important type of mass movement and a significant geomorphic process in mountain regions, frequently causing serious damage to settlements and transportation infrastructure (e.g. Davies, 1997; Korup and Clague, 2009; Takahashi, 2014; Cui et al., 2015). Debris flows are usually triggered by heavy rainfall and/or snowmelt; however, debris flows with large volumes can also transform from landslide dam collapses, avalanches or landslides from slope failures in their source area, and such events can have unusually high velocity, long travel distance and thus more destructive potential than smaller events (Iverson et al., 1997; Takahashi, 2014; Davies, 2014). It has long been accepted that debris flows enlarge their volumes and increase their destructive power by entraining the underlying sediments as they flow down steep slopes and channels (Hungr and Evans, 2004; Iverson, 2012).

The Yarlung Tsangpo (hereafter simply called the Yarlung River, Fig. 1) shows evidence of its ability to erode its channel and transport sediment during the last 1 Ma, especially in its knickpoint reach where the Namche Barwa-Gyala Peri massif has been deeply incised (Finnegan et al., 2008; Zeitler et al., 2014). In the adjacent northeastern area, mass movements such as landslides and debris flows occur quite frequently

* Corresponding author at: University of Chinese Academy of Sciences, 19 Yuquan Road, Shijingshan District 100049, Beijing, China.
E-mail address: zengql@ucas.ac.cn (Q. Zeng).

https://doi.org/10.1016/j.enggeo.2017.12.013
Received 2 June 2017; Received in revised form 10 December 2017; Accepted 11 December 2017
Available online 12 December 2017
0013-7952/

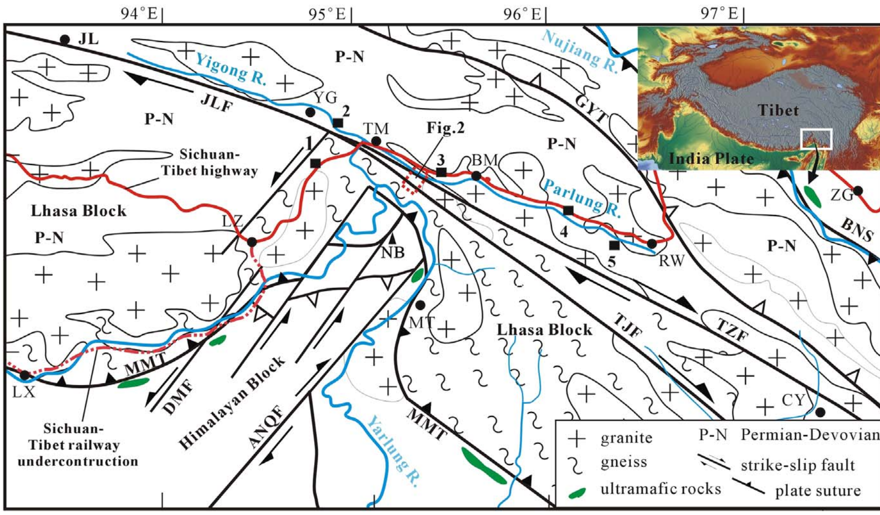

Fig. 1. Geological sketch map of the Eastern Himalaya Syntaxis (after Ding et al., 1995; Zeitler et al., 2014). (Abbrs.:Towns, LZ-Linzhi, JL-Jiali, LX-Langxian, MT-Motuo, TM-Tongmai, YG-Yigong, BM-Bomi, RW-Ranwu, ZG-Zuogong. Faults, JLF- Jiali fault; TZF-Tongmai Zhongkang fault; TJF-Tongmai Jinzhula fault; DMF-Dongjiu Milin fault; ANQF-Aniqiao fault; BNT-Banggongcuo-Nujiang thrust; MMT-main Motuo thrust; GYT-Guyu thrust. NB, Namche Barwa peak. Numbers: 1-Peilong debris flow; 2-Yigong rock avalanche-debris flow; 3-Guxiang debris flow; 4-Dongru debris flow; 5-Midui debris flow)

due to the combination of neotectonic deformation, intense precipitation and maritime monsoon glaciers (IMHE and ITS, 1999; Shang et al., 2005). With the effect of climatic warming there are increasing numbers and volumes of moraine-dammed lakes with the possibility of hazardous Glacial Lake Outburst Floods (GLOFs) in the Himalayas and Tibet (Costa and Schuster, 1988; Li and You, 1992; Richardson and Reynolds, 2000). Glacier retreat and permafrost degradation also expose more moraine and rock slopes to erosion by meltwater, which increases the frequency of mass movement like avalanches, landslides, collapses and debris flows (Gruber and Haeberli, 2007; Korup and Clague, 2009; Cui et al., 2015).

Many large-scale debris flows took place along Parlung River, a tributary of the Yarlung river (e.g. 1–5 in Fig. 1; IMHE and ITS, 1999). These large debris flows severely impacted the Sichuan-Tibet highway (State Highway G318) along the right bank of Parlung River in the past 60 years, and the highway was frequently closed for long periods. Therefore, from the early 1950s to the late 1990s, many researchers (e.g. Shi et al., 1964) carried out systematic field observations of the meltwater-triggered debris flows of Guxiang gully. In the 1970s, the Tibet Plateau Comprehensive Scientific Expedition Group conducted an investigation into the glacial debris flow hazard along the highway (Du et al., 1985). Since 1990, further research has been conducted into geohazards along the highway, obtaining valuable data and insights about their characteristics, mechanisms, and countermeasures (IMHE and ITS, 1999; Shang et al., 2005; Cui et al., 2015).

According to the China National Five-Year Plan, the Sichuan-Tibet railway (from Chengdu to Lhasa, Fig. 1), currently under construction from Lhasa to Linzhi along the Yarlung River, has been planned to be aligned along the Parlung River. It will traverse an area with high relief, high risk of earthquakes and high geohazards. On September 4 of 2007, and on July 25–31 and September 5–8 of 2010, three large debris flows took place in Tianmo gully, a tributary of the Parlung River (Figs. 1 & 2). These events provide a valuable opportunity to study the initiation mechanisms and geohazard cascades of debris flows, and their potential impacts on the proposed railway alignment. Ge et al. (2014), Zhang et al. (2015), and Deng et al. (2017) studied the meteorological triggers and obtained basic parameters of these events. The present paper, based on in-situ investigation of event evidence, resident interviews and analysis of remotely-sensed images of different periods, studies their geoenvironments, analyses their geohazard cascades and initiation mechanisms, and lastly puts forward some suggestions on minimizing the impacts of large debris flows to Sichuan-Tibet railway along Parlung River.

2. General settings

2.1. Geological conditions

The Parlung River is located in the northeastern part of the Eastern Himalayan Syntaxis. The area is mainly composed of Tongmai granite gneiss and quartz/biotite schist of the pre-Sinian system, which is the source rock of the Tianmo debris flows. More peripherally, there are Mesozoic sediment rocks and Yanshania granite (Figs. 1 & 2; Ding et al., 1995; Zeitler et al., 2014). The Jiali Fault (JLF) is an important active boundary fault with an average dextral strike-slip rate of 4 mm/yr. Its two branch faults, the Tongmai-Zhongkang fault (TZF) and the Tongmai-Jinzhula fault (TJF), pass through the upper and lower parts of Tianmo gully, respectively. The syntaxis region is highly seismic with 124 earthquakes of ML 4 or greater from 1950 to 1996, including the M_S 8.6 Motuo Earthquake in 1950 (Figs. 1 & 2; GRGST, 1995; IMHE and ITS, 1999; Ren et al., 2000; Zeng, 2007a). Both the active faults and the strong earthquakes reduce the integrity of rock mass and slope stability in the Tianmo watershed.

2.2. Geomorphology

Regionally the study area is located in the Parlung River, a deeply incised alpine gorge with extremely high erosion rates of > 5 mm/yr (Zeitler et al., 2014). The knickpoint of the Parlung River is near Guxiang, 15 km away from Tianmo gully (King et al., 2016). The mountain ridges of Parlung River are generally around an altitude of 5000 m with modern maritime glaciers. As a southern tributary of Parlung River, the Tianmo watershed originates from its southern range - Kangri Karpo mountain - and is shaped like an inclined bottle, with an area of 18.6 km^2 and a maximum height difference of 3190 m. The main channel is about 5.1 km long with an average gradient of 25.9%.

The Tianmo watershed can be divided into 3 zones (Figs. 2 & 3):

(i) The residual ancient-cirque zone, where the glacier is about 1.45 km^2 in area and the cirque slope is about 27°. Notably, there are some regions of exposed bedrock and moraine due to recent deglaciation.
(ii) The V-shaped transportation zone, where the channel is 3.65 km long and 16° in average slope. Both sides of the valley have an average slope angle of 32°~36°. The channel is incised into glacial tills and colluviums.
(iii) The alluvial terrace deposit zone, from the outlet of Tianmo gully to Parlung River. It is relatively flat (9°) and formed by multiple deposits of past debris flows, and was occupied by houses and

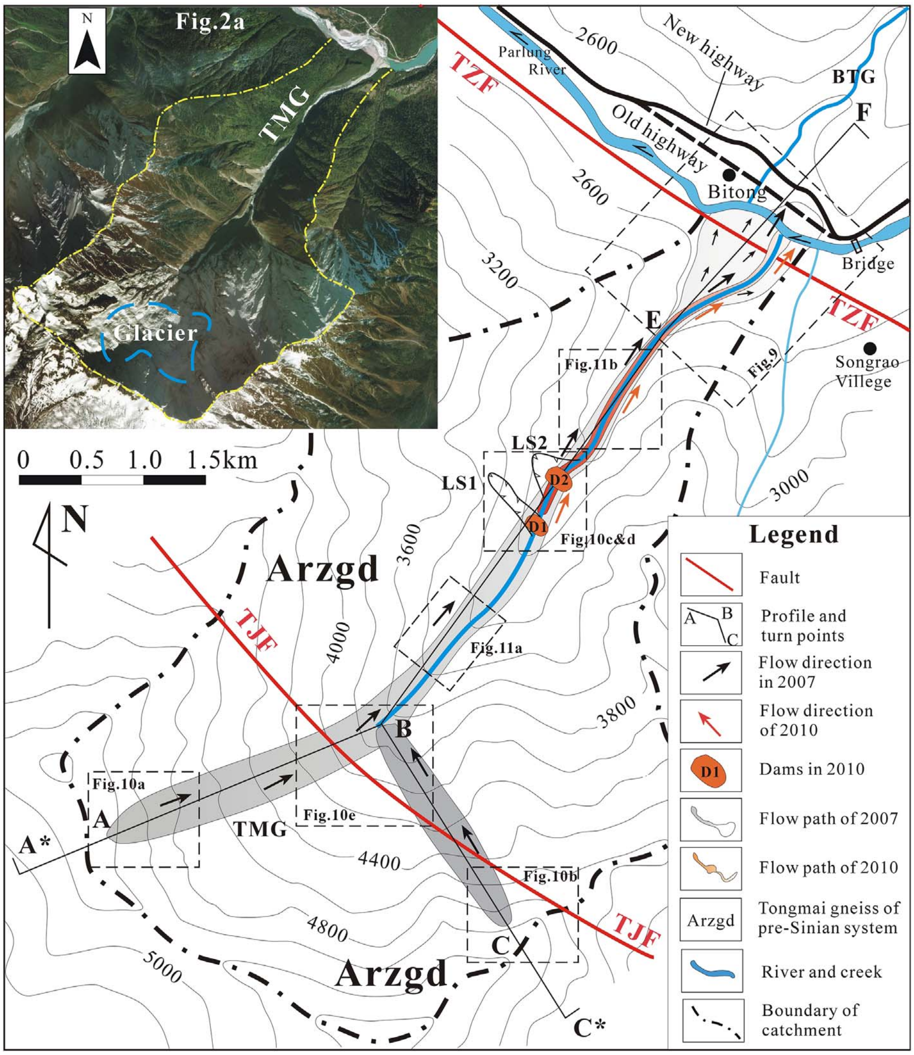

Fig. 2. Topographic and geological sketch map of Tianmo gully.
a shows the satellite image from ArcMap after 2010 debris flows but unknown exact time. Abbrs.:TMG-Tianmo gully, BTG-Bitong gully. A* and C* are the start points of the profile, A and C are the peak points of the ridge. B-conjunction point of two main sub-gullies. D1 and D2 are the dammed points. E is the outlet point. TZF & TJF as showed in Fig. 1.

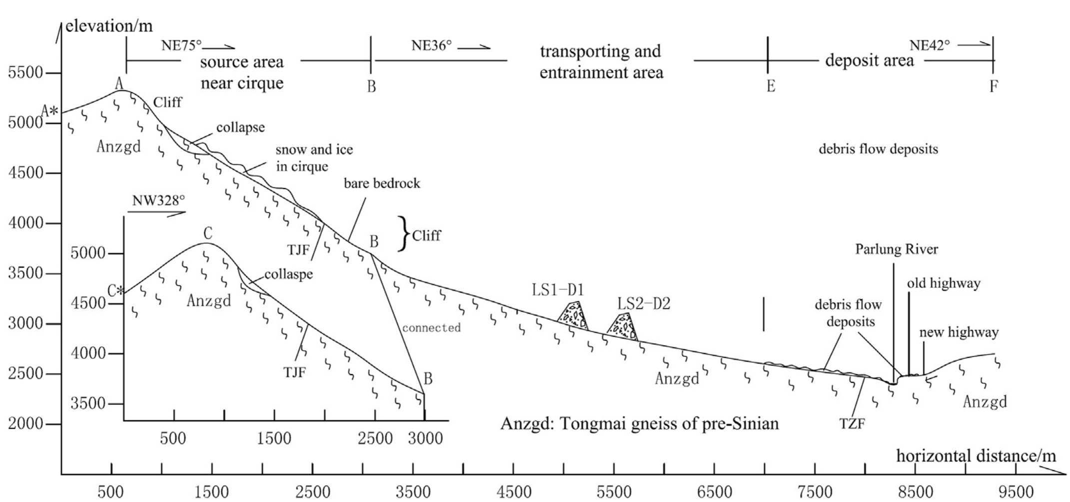

Fig. 3. Engineering geological sketch profile of Tianmo gully.
The C*-C-B profile connects with the main profile at point B. LS1-D1 and LS2-D2 show the landslide-dams by LS1 landslide and LS2 landslide both developed in 2010. TZF & TJF as showed in Figs. 1 and 2.

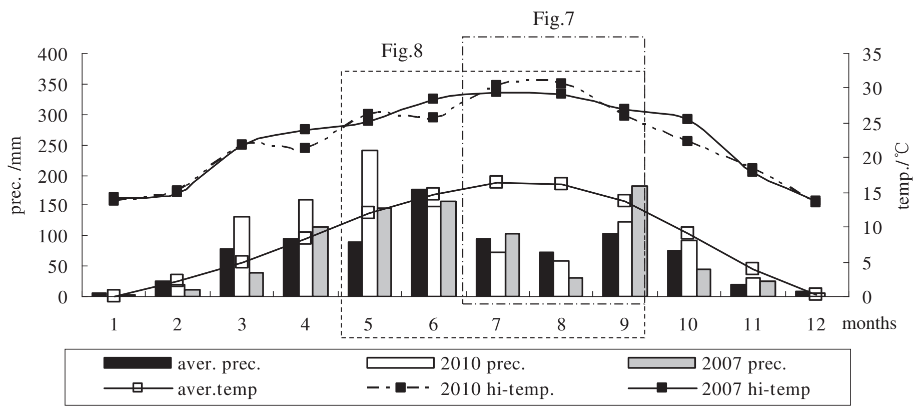

Fig. 4. Annual average monthly meteorological data and the corresponding data in 2007 and 2010.
Data from Bomi meteorological station. The two dashed rectangles show the scopes of detailed meteorological information in Fig. 7 for the 2007 debris flow, and in Fig. 8 for the 2010 debris flow.

farmland before the 2007 debris flow event.

2.3. Climate and precipitation

The climate of the Parlung watershed is mainly affected by the Indian monsoon, which transports the warm humid airflow along the Brahmaputra - Yarlung River and brings precipitation of 1100–1400 mm/a in Tongmai and Yigong but 700–900 mm/a in Jiali and Ranwu. Moreover, due to the high precipitation and the favorable topographic conditions, the Parlung River catchment hosts about 1320 modern maritime monsoonal glaciers with a total area of 2655 km^2 in its southern range (Kangri Karpo mountain) (Li et al., 1986; Mi et al., 2002). Tianmo gully is about 45 km northwest of Bomi town and about 26 km southeast of Tongmai village. Bomi national weather station has been the only station in the Parlung watershed since 1953, but there are some climate data from 1964 in Guxiang gully. The mean annual precipitation in Bomi is 906.5 mm, and the mean annual temperature is 11.9 °C (Fig. 4).

The mean air temperature increased 1.5 °C from 1970 to 2014, and remarkable deglaciation also took place in Tianmo gully, the ice area decreasing from 1.77 km^2 in 2000 to 1.42 km^2 in 2013. The annual precipitation and the summer rainfall have appeared abnormal since 2000 (Deng et al., 2017). Air temperature reduces with elevation at a rate of 0.54 °C per 100 m, and glacier meltwater comprises about 10% of total annual runoff (Zhang et al., 2015).

2.4. Geohazard history

Strong coupling of the above endogenic and exogenic geological actions controls the development, type, size and frequency of geohazards in the Parlung River (IMHE and ITS, 1999). 67 debris flow gullies have been recorded, mostly of glacial origin. Some were super-large and catastrophic like the 1953 Guxiang debris flow (Fig. 1; Shi et al., 1964). Smaller debris flows take place every year in the tributaries of Parlung River; for example, during wet season of 2005 debris flows took place in 14 gullies (Zeng, 2007a), 3 big debris flows of 3–4 × 10^5 m^3 occurred in Guxiang gully in July 30 and August 6, 2005 (Lu et al., 2006), and 5 debris flows developed during September 4–9, 2007 (Deng et al., 2017).

3. Event summaries

At about 7:20 pm on September 4, 2007, a debris flow occurred in Tianmo gully and lasted for approximately 40 min (Fig. 5); hereafter this event is referred to as the 2007 DF. Some debris crossed the Parlung River and flowed up onto the terrace carrying the Sichuan-Tibet highway. The total solid material transported in the debris flow was about 7.6 × 10^5 m^3. The event caused 1 death, 7 disappeared and 9 injured. About 2 ha of farmland 2 houses on the south terrace were buried. The highway reopened 43 h later.

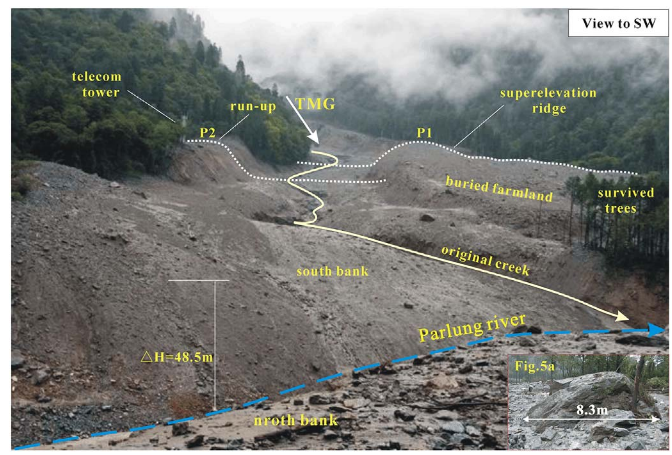

Fig. 5. The scene of the debris flow in September 4, 2007, Tianmo gully.
TMG-Tianmo gully. Profiles P1 & P2 are used for velocity estimation from superelevation or run-up. Fig. 5a shows the largest block transferred to the north bank with scale of 8.3 m × 6.6 m × 3.5 m. The height difference from river bed to bank top is 48.5 m. The telecom tower is 20 m high.

During July 25–31, 2010, at least 4 medium-scale debris flows occurred in Tianmo gully (Fig. 6; hereafter this event is called the 2010 DF1). The total transported solid material was about 2.1 × 10^5 m^3. The 2010 DF1 blocked the Parlung River for 15 min and breached quickly. The north river bank was seriously eroded by the outbreak flood and retreated about 110 m, and about 5.9 × 10^6 m^3 of terrace sediments were eroded. This event destroyed a 450 m length of highway and the 76 m long Bitong bridge (Fig. 6a).

In addition, in September 5–8, 2010, another debris flow occurred in Tianmo Gully almost as big as that in July (hereafter this event is called the 2010 DF2). The bed level of Parlung River was further increased, and the Songrao suspension bridge was completely submerged (shown in NE corner of Fig. 2). It is difficult to distinguish the two events in 2010 on the basis of their channel deposits. The 2010 debris flows in the Tianmo gully closed the Sichuan-Tibet highway for 16 days and caused direct economic loss of > 19.7 million RMB.

4. Differences between the 2007 DF and 2010 DFs

Based on field investigation and analysis, it is suggested that the 2007 DF and the 2010 DFs in Tianmo gully differ from each other in antecedent temperature and precipitation, flow process, number of surges and velocity.

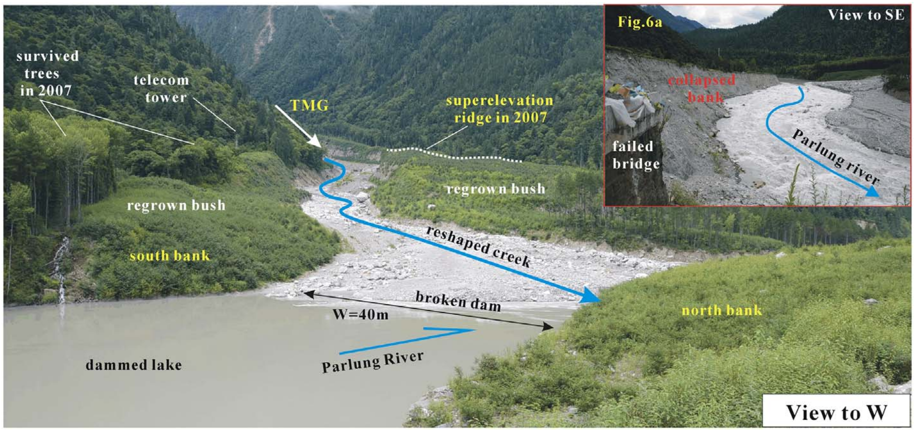

Fig. 6. The scene of the 2010 debris flows in Tianmo gully. Pictures were taken in July 2011.
a. shows the bank, highway and bridge failure. The impounded water was due to the remains of the partially broken dam.

4.1. Differences in meteorological trigger

The monthly precipitation in July 2007 was 102.5 mm, only 8.7 mm more than the historical average. There were 27 rain days and the monthly insolation was only 86.6 h (Fig. 7). In August the rainfall abruptly reduced to only 31.1 mm and is only 47% of the historical average, and the mean monthly temperature was 1.5° higher than the average (Fig. 4). Rain began on September 2 and lasted to September 16, with a total rainfall of 181 mm, with an especially high total of 20.4 mm in September 4 when the debris flow took place (Fig. 7). Moreover, based on a previous study in Guxiang (IMHE and ITS, 1999), the precipitation in the cirque area would have been much larger than in the outlet of Tianmo gully and the temperature lower. Therefore, the weather data prior to the 2007 DF occurrence suggests a strong wet-dry-wet alternation, which suggests a large amount of ice- and snow-melt in the cirque area, and thermal expansion and contraction in the outcropped rock and moraine deposits. These would reduce their stability.

In March, April and May 2010, precipitation was 1.66, 1.69 and 2.71 times larger than their historical averages. Precipitation in May reached 241 mm (Fig. 4). In July 2010, however, it was hot with only 72.9 mm of rainfall, 78% of the historical average. Another abnormality is the high temperature and large temperature anomaly from July to August (Fig. 8); it reached 29.4 °C in July 24, and the rainfall was only 2.7 mm from July 19 to 24. Therefore, it is suggested that the high Spring precipitation caused large snow and ice accumulations, and the high temperature Summer caused them to melt to form large meltwater discharge. Exacerbated by the 7.7 mm rainfall in July 25, the big discharge would reduce ground stability. On September 4–9 there was a concentrated rainfall of 79 mm (Fig. 8), which was when the 2010 DF2 occurred.

4.2. Differences in surge number, volume and flow process

Based on the field investigations and local interviews, the whole volume of the 2007 event was completely delivered in a single surge and lasted for only 40 min. Although the total precipitation from September 5 to 16 was 152.5 mm, and on September 5 and 6 19 mm and 24.2 mm fell respectively (Fig. 7), no further debris flows took place. The channel bank within the valley was seriously eroded by the debris flow and new scarps could be widely seen in pictures. Moreover, the debris flow did not follow the channel, but spread like a fan from the outlet of the gully, partially overflowing onto the left terrace to bury the farmland and the houses. Some debris even crossed the river and climbed up a 48.5 m high river bank onto the north terrace to cover the highway (Fig. 5). It is estimated that a total of about 7.6×10^5 m^3 of debris was output.

By contrast, the 2010 DF1 consisted of dozen surges from 25 to 31 of July, and debris flow surges also flowed out of the gully in July 27–28 even without rainfall (Fig. 8). The largest debris flow was in July 31 but with daily rainfall of only 8 mm. The debris flows were completely confined within the channel (Fig. 6), and moved into the Parlung river and blocked it step by step. The total output solid material was about 2.1×10^5 m^3. According to the incomplete news reports, there were at least 4 debris flows of approximately 2×10^4 m^3 each. Additionally, the 2010 DF2 in September 5–8 also had several surges and lasted 3–4 days. The surges of the 2010 DF2 had similar size to the 2010 DF1 events that occurred in July, and further enlarged the barrier lake to submerge the suspension bridge (Fig. 9).

It is notable that, although the solid material volume transferred by the 2007 DF was larger than that of the 2010 DF1, the Parlung River was not blocked in 2007. The 2007 DF flowed over the wide terrace (still 250 m wide near the river), which reduced the debris volume moving into the river and allowed some debris to be quickly taken away by the river (Figs. 5 and 9). Thus only a submerged dam was formed but

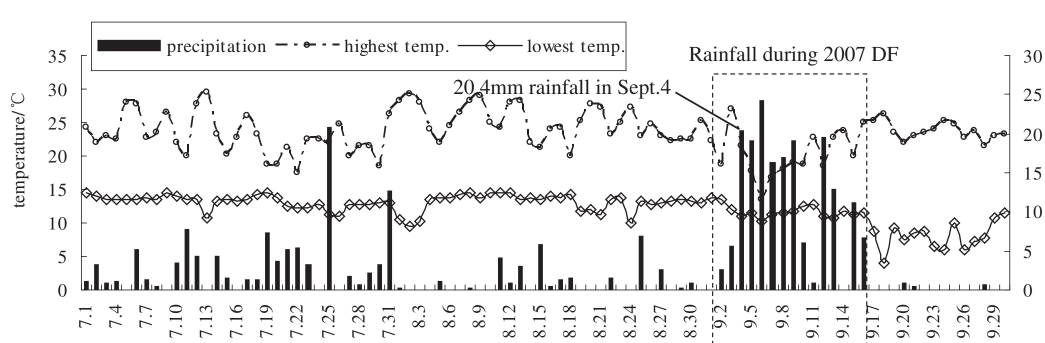

Fig. 7. Precipitation and temperature data from August to September in 2007 showing the climatic conditions for the 2007 DF.
Data from Bomi meteorological station.

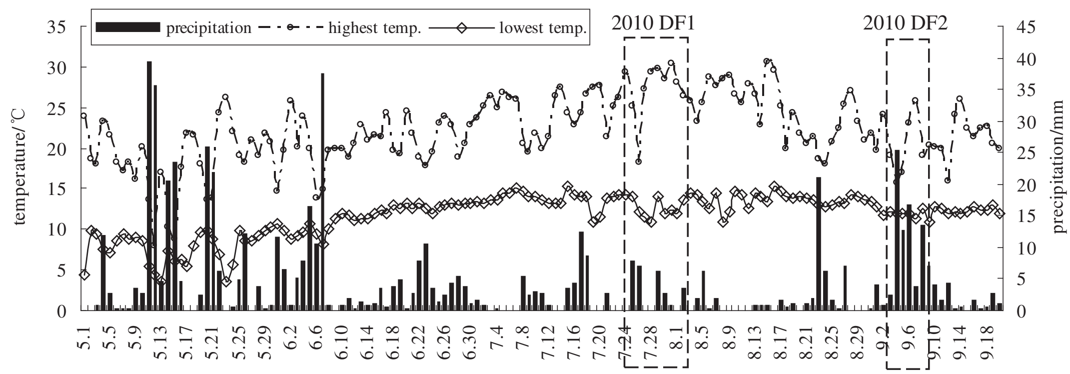

Fig. 8. Precipitation and temperature data from May to September in 2010 showing the climatic conditions for the 2010 DF1 and DF2.
Data from Bomi meteorological station.

it did not block or dam Parlung River. By contrast, the smaller 2010 DF formed a temporary dam, probably because (i) the debris flow moved quickly along the existing channel into the river (Figs. 6 and 9); and (ii) some bed aggradation from the 2007 event may still have been present.

4.3. Differences in velocity

Many indications suggest that the 2007 DF ran out of Tianmo gully at high speed (Fig. 9). Firstly, it caused lateral overflow or superelevation in a slightly curved channel just at the outlet of the gully (P1 & P2 in Figs. 5 & 9). The debris flow was too fast for the villagers living on the terrace to escape being buried. Secondly, part of the debris flow crossed the 75 m–85 m wide riverbed and formed a deposit 250 m long and 170 m wide with a volume of 1.06×10^5 m^3 on top of the 48.5 m high river bank (Fig. 5), killing a cyclist on the highway. Trees beside the highway were destroyed, some trunks being broken at middle height. Lastly, many big gneiss blocks were deposited on the highway side, the biggest being 8.3 m × 6.6 m × 3.5 m, weighing nearly 350 tons (Fig. 5a).

Back-calculation based on the gravity resistance equation has been proposed and widely used to obtain the minimum velocity required for a flow to climb to a certain height (Eq. (1); Chow, 1959; Johnson and Rodine, 1984; Rickenmann, 1999; Evans et al., 2001; Jibson et al., 2006).

$$v = \sqrt{2gh} \tag{1}$$

A different back-calculation using superelevation could has been believed to be presently the most accurate way to estimate the front velocity of debris flow (Eq. (2); Iverson et al., 1994; Prochaska et al., 2008; Scheidl et al., 2015), which is commonly based on the forced vortex equation.

$$v = \sqrt{\frac{R_c g}{k}\frac{\Delta h}{b}} \tag{2}$$

where v is the mean flow velocity in meters per second, Δh is the superelevation height in meters, b is the flow width, and g is the acceleration of gravity (9.81 m/s^2). R_C is the channel's radius of curvature, and k is the correction factor for viscosity and vertical sorting. And g should be replaced by $g^* = g\cos\theta$ if the channel slope is > 15° where θ is the channel slope.

Ascending a bank 48.5 m high, Eq. (1) gives a minimum velocity of 30.8 m/s or about 110 km/h. If considering the 170 m spreading distance of debris away from the bank, and other resisting and collisional forces consuming kinematic energy, the actual velocity of the 2007 DF

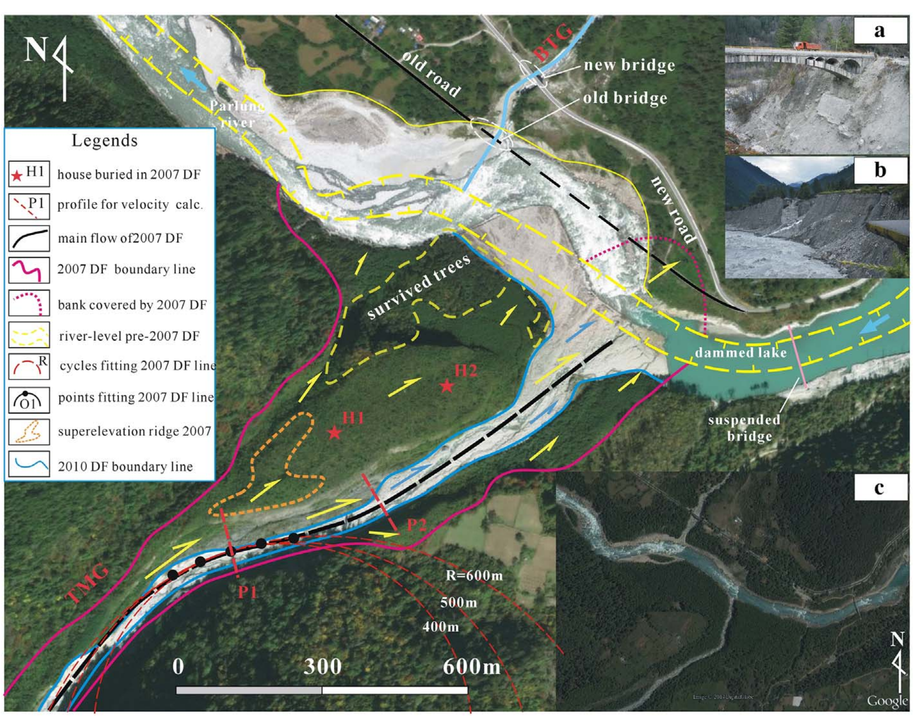

Fig. 9. Satellite image outside the Tianmo gully after the 2010 DF.
It shows the flow curve, deposit and dammed lake of the two debris events. The base image is from ArcMap Online which taken after the 2010 DF. a-Bitong bridge taken in 2006 and showing the deep erosion to the debris flow fan by the debris flows in 2005. b-the failure of river bank, highway and Bitong bridge. c-Google Earth image taken in April 2006 before the debris flows and showing the original status. TMG-Tianmo gully, BTG-Bitong gully.

at the river bank should be considerably > 30.8 m/s.

As emphasized by Prochaska et al. (2008), the required channel radius of curvature for Eq. (2) is subjectively estimated, so there could be an error of 25% in the channel curvature. At P1 in Fig. 9 where the channel cross-section was measured, Tianmo gully turns right and the debris flow overflowed onto the left farmland terrace due to superelevation, while many trees survived on the inner bank. Following the radius estimation method suggested by Prochaska et al. (2008), 5 points with 50 m spacing on the middle flow line in a 1:9000-scale satellite image were tested to fit circles and obtain a radius. Among the 3 trial radii of 400 m, 500 m and 600 m, $R = 600$ m could fit all the 5 points while the others only fit 3–4 points. The parameters for Eq. (2) were measured at position P1. The channel slope (θ) is 10°, the flow width (b) is 58 m, and the superelevation height $\triangle h$ is 15 m. The banking angle β is about 14.5°. Thus according to Eq. (2), the velocity is calculated as 38.8 m/s or about 140 km/h assuming $k = 1$. Scheidl et al. (2015) discussed k in detail and studied with laboratory experiments, and it varies between 1 and 5. The velocity becomes 24.5 m/s if taking $k = 2.5$, which does not match the result from the run-up calculation.

Additionally, after the debris flow collided with the left bank in the outlet, some debris changed direction to flow east and climbed up ~24 m onto the opposite terrace at P2 where there was a 20 m high telecom tower (Figs. 9 and 5). Based on Eq. (1), the velocity of this part of debris is estimated as 21.7 m/s.

The velocity of the 2010 DF was much lower than the 30–40 m/s of the 2007 DF. Although there were some super-elevation traces in the gully outlet, the debris flows were completely confined within the existing channel. At the channel section ~300 m away from P3 in Fig. 9, Ge et al. (2014) obtained a peak velocity of 12.7 m/s by the modified Manning formula and a peak discharge of 3334 m^3/s for the 2010 DF. These are close to the values of 12.98–13.41 m/s and 3081–3181 m^3/s calculated by Zhang et al. (2015) for the 2007 DF by the local empirical formulas.

5. Debris flow analysis

The significant differences between the 2007 DF and the 2010 DFs imply that they probably originated in different ways and involved different processes within the valley.

5.1. Initiation of the 2007 DF and 2010 DFs

Due to the complicated and dangerous conditions, it was difficult to access the inner and higher part of the valley during the field investigations. By partial field trips and analyzing photos taken in 2006 and soon after the event, it was found that channel banks in the transportation zone, mainly composed of moraine, were eroded with fresh scarps (Zhou, 2007; Fig. 10). New bare rock just below the cirque was also identified in the 2009 TM image (Deng et al., 2017). Some rock and moraine debris were deposited on the western glacier of the cirque (Fig. 10a), and there were fresh scarps on the eastern glacier of the cirque (Fig. 10b). Therefore, there is a high possibility that the 2007 DF initiated from the collapse of the bedrock or/and moraine near the cirque glacier, but it is difficult to conclude which part failed in 2007 due to shortage of clear satellite images and inaccessibility.

Such a fractured rock or moraine collapse could be due to high rainfall after long-term dry weather. There has been rapid ice mass loss and glacier retreat since the 1970s in the eastern Nyainqentanglha range of SE Tibetan Plateau, e.g., 4 glacier terminals in the southeast head of the Parlung river thinned 3.75 m to 5.2 m and retreated 15 m to 19 m from May 2006 to May 2007 (Yang et al., 2008). The Tianmo cirque glacier area decreased 13.6% from 2000 to 2006, while the snow area increased 25.8% based on TM image interpretation (Deng et al., 2017). The fast retreat of the glacier uncovered the former buried fractured rock and the moraine, which then experienced stronger physical weathering and erosion action than before (Fig. 10e). Additionally, glacial debuttressing reduced the slope stability.

Through comparison with the satellite images and photos taken before 2007 and after the 2010 debris flow, two new landslides were identified in the left slope of Tianmo gulley (Fig. 10c & d), which occurred during the 2010 DFs. They are 1870 m and 1750 m away from the valley outlet with volumes of 1.72×10^5 m^3 and 3.26×10^5 m^3, respectively (hereafter referred to as LS1 and LS2, respectively). Both landslides originated from a debris slope composed of moraine and colluvium. Their failure probably involved erosion by high meltwater due to hot weather in May and June, the impact of meltwater or snow avalanches from the small gully opposite, and the erosion of the 2007 DF. Both landslides blocked the channel and breached. It is suggested that the 2010 DFs both initiated from the breach of these landslide dams, but the corresponding relationship between LS1, LS2 and DF1, DF2 is unknown due to lack of evidence.

Generally, natural landslide dams do not fail and disappear

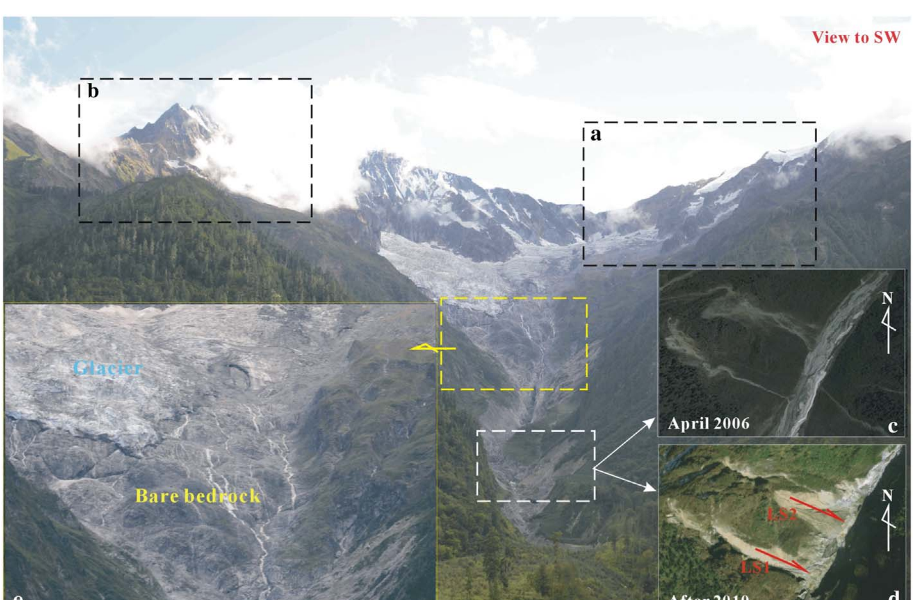

Fig. 10. Sources of avalanches and landslides of debris flows in 2007 and 2010.
a and b -the possible positions of avalanches for the 2007 DF; c and d -the landslides for the 2010 DFs; d also from ArcMap online and it was taken after the 2010 DFs. e-serious glacier retreat with bare bedrock under the cirque.

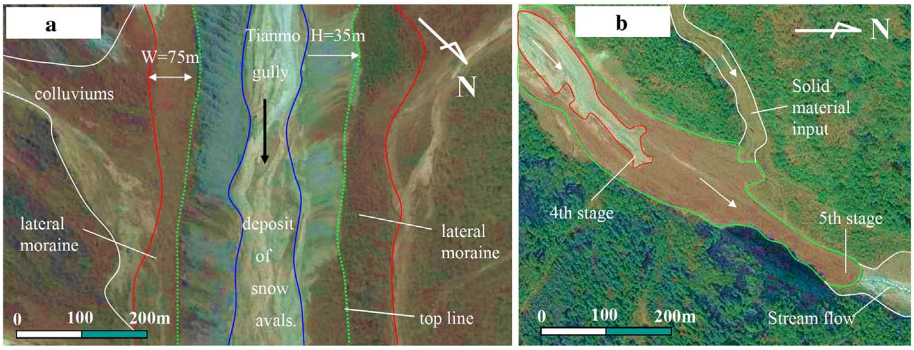

Fig. 11. The moraine channel banks and the multi-stage ice-snow avalanches developed in Tianmo gully. (The images were from Google Earth taken in April 2006. a shows the channel bank composed mainly by the loose moraine and the slope colluviums, and the snow avalanches in channel bottom. b shows the outmost two stages of snow-ice avalanche deposits, where lots of debris is on the surface but with stream underflow. Position index in Fig. 2).

completely in a single event, but have some residual sediments after the initial failure, as in the Yigong landslide in 2000 (Delaney and Evans, 2015) and the Tangjiashan landslide in 2008 (Liu et al., 2009). Observations in Guxiang gully during the summer 1964 suggested a close relationship between moraine collapse and the occurrence of debris flows; 645 collapses of moraine slope took place within 60 days and caused 505 debris flow events (IMHE and ITS, 1999). Such conditions also took place in the 2010 DFs. The 2010 DF1 lasted from July 25 to 31, and the 2010 DF2 lasted from September 5 to 8. The continuous debris flow surges after the first breach were due to the step-by-step collapses of the residual landslide dams. The size and surge frequency of every debris flow are related to the dam collapse and rainfall/meltwater occurrence (Costa and Schuster, 1988).

5.2. Entrainment of the 2007 DF and 2010 DFs

The three debris flows are much larger than their landslide origins. Entrainment can result from the erosion of bed material or the collapse of valley banks, causing the flow mass to grow much larger than its initially mobilized source volume before it finally deposits (Hungr and Evans, 2004; Breien et al., 2008). High resolution satellite images by Google Earth on May 9, 2000 and April 30, 2006, as well as pictures taken by authors in March 2006, show that there were plenty of loose materials for debris flow to entrain.

The primary sediment source is the lateral moraine of Last Glacial and New Ice Age on the main channel banks (about 1.1 km long; Fig. 11a). The moraine bank is about 35 m high and 20–80 m wide at the top with a large active volume estimated at about 2×10^6 m^3. Comparing the pictures taken in 2006 with those in 2009, this moraine bank was severely eroded during the 2007 DF. Secondly, a large amount of snow or ice avalanches masses in the gully bottom. Within the 3.65 km long main valley from the rock scarp to the outlet, 5 stages of ice/snow avalanche deposit could be identified in the 2006 Google Earth image (Fig. 11b) and these are 0.2 km, 1.1 km, 2.0 km, 2.7 km and 3.1 km away from Point B, individually. There is much rock debris on or within the ice/snow avalanche deposits, with a stream flowing out from the 5th stage. Additionally, there are also lots of fluvial and alluvial deposits in the channel, which were deeply eroded by the 2010 DFs.

5.3. Cascade of the 2007 DF and 2010 DFs

Based on the above description, the geological progress and geohazard cascade of the 3 debris flows are summarized:

The cirque glacier of Tianmo gully has greatly retreated since the 1970s. Large areas of fractured bedrock and moraine are no longer covered by the glacier, exposing them to long-term thermal expansion and contraction and reduced stability. After the wet weather of July 2007 followed by dry warm weather in August, a concentrated rainfall of bigger than 20.4 mm/d finally triggered the collapse of the periglacial slope in the cirque area on September 4, 2007. The collapsed mass descended and accelerated, reaching a high speed before moving to the main valley. During motion large volumes of sediments and fluids were entrained, including glacial ice, snow, moraine, colluvium and water, and the final event had the saturated consistency typical of a debris-flow. When the mixture left the gulley outlet with a velocity of ~40 m/s, some overflowed onto the ancient alluvial terrace and buried the houses and the farmland, some moved at high speed into the river and ascended the high river bank at 30 m/s, and some deposited in the river and aggraded the riverbed.

Probably impacted by the 2007 DF and water flow, the left bank slope was close to instability. From March to May of 2010, there was much more precipitation (including snow at high altitude) than before, but it became abnormally hot and very dry in July 2010. Meltwater flow further eroded the slope base and triggered the landslide (LS1 or LS2). The landslide blocked channel to form a landslide-dam. The dam then breached due to the continuing rain and melt water, generating a multi-surge debris flow which moved into Parlung River along the original channel. The debris flow formed another temporary dam in the Parlung river, and the following dam-breach flood eroded the north terrace causing the failure of river bank and the highway bridge and road there. In September 4 of 2010, a 24-h rainfall of 25.3 mm triggered another landslide to block the valley, and the dam breached on September 5 to form another multi-surge and multi-day debris flow. The debris surges flowing into the river enlarged the barrier lake.

5.4. Analysis of debris flow in Parlung River

The active tectonics, topography, meteorological and hydrological conditions provided suitable endogenic and exogenic conditions for the occurrence of slope collapse, landslide and debris flow in Parlung River. Three main mechanical causes of debris flow initiation were classified by Takahashi (2014): (1) surface runoff makes gully bed deposits unstable to develop into a debris flow; (2) falling debris mixes with water in a gully and transforms into debris flow; and (3) the collapse of a debris dam suddenly causes a debris flow.

Although the 2007 DF and the 2010 DFs were both initiated by landslides or avalanches, their subsequent processes were different. In the 2007 event the landslide mass of fractured bedrock or moraine passed completely through the gully without stopping. It was essentially a rock or debris avalanche, but many such debris avalanches transform into large debris flows (Takahashi, 2014). It entrained glacial ice, snow, moraine, colluviums and water along its path, similarly to the Yigong rock avalanche – debris flow. It is consistent with the second mechanism of Takahashi (2014). However in the 2010 events, the landslides developed in the main valley bank, deposited and blocked the valley. The landslide dam then failed due to the upstream impounded water overtopping the dam crest or piping (Takahashi's type 3). The formation mechanism of the debris flow and the process cascade are summarized in Fig. 12.

Moreover, as already mentioned above, there are many old and modern large debris flow deposits in other tributaries of Parlung River,

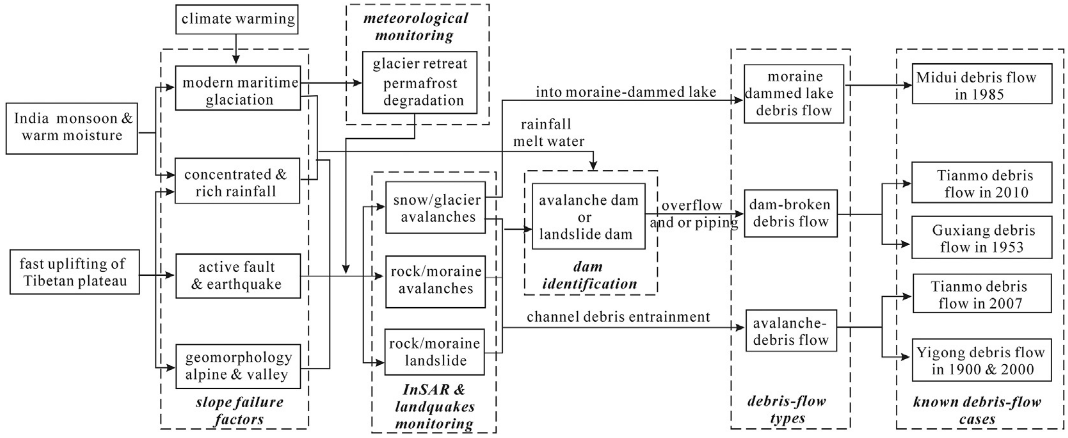

Fig. 12. The mechanism of debris flow initiation and the geohazard cascades in Parlung River.

in similar geo-environments to the Tianmo debris flows. Examples are the huge debris flow deposits along the section from Bomi town to Guxiang village (Zeng et al., 2007b), and the modern large debris flows that took place in Guxiang gully in 1953, Dongru gully in 1975, Peilong gully from 1983 to 1985, and Zhamu gully in 2000 (Shi et al., 1964; Lü and Li, 1989; Yang, 1991; Li and You, 1992; Zhu et al., 2000; Shang et al., 2003; Wu et al., 2005; Fig. 1). These all have the common characteristics of debris flows developing from rock avalanches. Some (e.g., the 2000 Yigong avalanche – debris flow) are like the 2007 DF of Tianmo, but most (e.g., the 1953 Guxiang debris flow) are like the 2010 DFs.

6. Discussion

In this study, the velocity of 12–14 m/s for the 2010 DFs is consistent with its characteristics of flow process and the subsequent river blockage. Such a velocity is normal and understandable in SE Tibet and SW China, e.g., 6.0–9.1 m/s for Guxiang gully by model testing after its outlet (Cheng et al., 1997), 7.44–9.57 m/s for Peilong gully by modified Manning formula near the junction to the river (IMHE and ITS, 1999), 3.7–10.0 m/s for Jiangjia gully by a dataset of 50 debris flow observations in 1970 (Wu et al., 1990), and 9.7–11 m/s of peak velocity for 2010 Zhouqu debris flow (Tang et al., 2011).

However, the velocity of the 2007 DF downstream the outlet is estimated 30–40 m/s using back-calculation of superelevation and running-up, which seems very high for a debris flow. As described above, the 2007 DF was essentially a fractured rock or moraine debris avalanche originating from the high periglacial cirque with a height difference of > 850 m over its flow path, perhaps explaining high speed. Previous accumulated snow avalanches and ice in the channel bottom were entrained into the flow and maintained its high velocity. Meanwhile, the avalanche block transformed into debris flow during motion by entraining sediments, ice, snow and water. Takahashi (2014) recognized such an avalanche as an important debris flow initiation mechanism.

The 2007 DF behaved similarly to the adjacent Yigong avalanche - debris flow of 2000, apart from the scale. The mean velocity of Yigong event was 37–39 m/s according to Chai et al. (2001), 48 m/s for main rock avalanche and 16 m/s for later debris flow according to Ren et al. (2001), as well as the average velocity of 17.6 m from a DAN-W simulation according to Delaney and Evans (2015). Those data are of the same order as our estimated velocity for the 2007 DF. Moreover, in the 2010 Mount Meager rock slide – debris flow, the disintegrating mass reached 64 m/s at the conjunction (7.8 km away from the source) according to a superelevation back-calculation (Guthrie et al., 2012). Therefore, from the point view of an avalanche - debris flow, our estimated velocity of about 30–40 m/s for the 2007 debris flow at the exit of the curve is credible.

With warming temperatures, the glaciers of the Parlung watershed have experienced rapid glacial retreat including area reduction, mass deficit and continued terminus retreat (Yang et al., 2016). The degradation of permafrost in periglacial rock and moraine as well as slope debuttressing would be expected to increase the susceptibility of slope failure in alpine areas (IMHE and ITS, 1999; Shang et al., 2003; Geertsema et al., 2006; Gruber and Haeberli, 2007; Huggel et al., 2012; Gariano and Guzzetti, 2016; Coe et al., 2017). Periglacial debris flows would be expected to become more active with higher frequency and higher probability of catastrophic disasters (Cui et al., 2015; Deng et al., 2017). This trend would put the coming Sichuan-Tibet railway along Parlung river at high risk in the future.

Therefore, with regard to the two main initiation mechanisms in Parlung River (i.e., landslide-induced debris flow and the natural-dam-failure debris flow) and their close relationship to the degradation of glacier and permafrost, monitoring providing early warning of their occurrence could be a feasible and effective mitigation method. However, the precise position of avalanche and landslide is usually unknown and beyond visual range, and we do not know when and where it will take place, or with what size, prior to the event. Traditional detection methods cannot match above requirements (Itakura et al., 2005).

Synthetic Aperture Radar interferometry (InSAR) is a potential technique which has made successful application in landslide, glacier and permafrost monitoring using multi-temporal radar data (Colesanti and Wasowski, 2006; Chen and Lin, 2012; Wasowski and Bovenga, 2014). Through the analysis of InSAR data in Parlung River, the rates of degradation of the regional glacier and permafrost could be measured, and a deformation rate map of the periglacial rock and moraine slope could be made. The areas most prone to landslide could thus be identified and monitored. Additionally, seismic signal of landslide and its propagation could be detected by local and regional stations, and rapid analysis of their kinematic and dynamic features undertaken (Deparis et al., 2008; Allstadt, 2013; Chao et al., 2017) to allow halting of traffic in safe areas. Therefore, the techniques of InSAR and seismology would be a great help to the knowledge of the landslide and the debris flow, but also to their early warning for the railway project.

7. Conclusions

Tianmo gully, a tributary of the Parlung River located at the front of the Eastern Himalaya Syntaxis, has complex geological structures and strong neotectonic deformation, a steep incised valley, a high-level cirque with a modern maritime glacier, and intense precipitation. Those geo-environmental characteristics and their strong interactions make it possible to back-analyze geohazards like the 2007 and 2010 debris

flows.

From the significant differences in meteorological trigger, output volume, surge numbers, flow process and velocity between these 3 debris flow events, it is concluded that the 2007 DF and 2010 DFs probably have different cascade processes although they both originated from landslides. The 2007 debris flow originated from a rock/moraine avalanche on the cirque edge, entrained snow and ice and ran directly through and out of the gully with a high speed (about 30–40 m/s) and so was able to cross the river and deposit large volumes of material on a bank 48.5 m high. The 2010 debris flows started from two landslides in the left channel bank which blocked the valley to create a dam. The multi-day, multi-surge debris flow due to the landslide dam breach ran down the river along the existing channel with a velocity of 12–14 m/s, but temporarily dammed Parlung River. The collapse of Bitong bridge and hundreds meters of highway road were caused by the outburst flood of the breach of Parlung River dam.

The factor common to other typical, large debris flows in the Parlung River area, including the three in Tianmo gully, is that they are either sourced from the rock/moraine avalanches from high mountain ridges, or from the collapse of a landslide dam. The application of new techniques of remote sensing and detecting using InSAR and seismology could be promising in the mitigation of large debris flow risks to the coming Sichuan-Tibet railway.

Acknowledgements

The work is supported by financial grants from National Natural Scientific Foundation of China (41772382, 41402269, 40972199). The corresponding author thanks for the support of China Scholarship Council for his visit to the University of Canterbury, New Zealand. Special thanks to the Meteorological Bureau of Bomi for the meteorological data. The authors thank sincerely to Prof. Zhifa Yang, Yanjun Shang, Zhongqi Yue, Yuanze Zhou and Dr Luqing Zhang for providing valuable discussions on the manuscript structure. We wish to acknowledge the editors of Engineering Geology and the reviewers for their constructive comments, which help improve the contents and presentation of the manuscript.

References

Allstadt, K., 2013. Extracting source characteristics and dynamics of the August 2010 Mount Meager landslide from broadband seismograms. J. Geophys. Res. 118, 1472–1490.
Breien, H., Fabio, D., Elverhøi, A., Høeg, K., 2008. Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides 5, 271–280.
Chai, H.J., Wang, S.T., Xu, Q., Huang, R.Q., Fan, X.D., 2001. Numerical simulation on overall progress of Yigong slump at Bomi, Tibet. J. Geol. Hazard. Environ. Press. 12 (2), 1–3 (In Chinese).
Chao, W.A., Wu, Y.M., Zhao, L., Chen, H., Chen, Y.G., Chang, J.M., 2017. A first near real-time seismology-based landquake monitoring system. Sci. Rep. 7, 43510. http://dx.doi.org/10.1038/srep43510.
Chen, F., Lin, H., 2012. Surface deformation detected by the space-observed small baseline SAR interferometry over permafrost environment in Tibet Plateau, China. Cryospere Discuss. 6, 4071–4099.
Cheng, Z.L., Liu, L., You, Y., 1997. Debris flow velocity of Guxiang ravine, Xizang. Mountain Res. 15 (4), 293–295 (In Chinese).
Chow, V.T., 1959. Open-channel Hydraulics. McGraw-Hill, New York, pp. 680.
Coe, J.A., Bessette-Kirton, E.K., Geertsema, M., 2017. Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. Landslides. http://dx.doi.org/10.1007/s10346-017-0879-7.
Colesanti, C., Wasowski, J., 2006. Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. Eng. Geol. 88, 173–199.
Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. GSA Bull. 100, 1054–1068.
Cui, P., Su, F.H., Zou, Q., Chen, N.S., Zhang, Y.L., 2015. Risk assessment and disaster reduction strategies for mountainous and meteorological hazards in Tibetan plateau. Chin. Sci. Bull. 60 (32), 3067–3077.
Davies, T.R.H., 1997. Using hydroscience and hydrotechnical engineering to reduce debris flow hazards. In: Chen, C.L. (Ed.), Debris-flow Hazard Mitigation: Mechanics, Prediction and Assessment. ASCE, New York, pp. 787–810.
Davies, T.R.H., 2014. In: Davies, T.R.H. (Ed.), Landslide Hazards, Risk and Disasters. Introduction. Elsevier, Amsterdam, pp. P1–38.
Delaney, K.B., Evans, S.G., 2015. The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: review, remote sensing analysis, and process modeling. Geomorphology 246, 377–393.
Deng, M.F., Chen, N.S., Liu, M., 2017. Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo valley, south-eastern Tibetan Plateau. Nat. Hazards Earth Syst. Sci. 17, 345–356.
Deparis, J., Jongmans, D., Cotton, F., et al., 2008. Analysis of rock-fall and rock-fall avalanche seismograms in the French Alps. Bull. Seis. Soc. Am. 98 (4), 1781–1796.
Ding, L., Zhong, D.L., Pan, Y.S., et al., 1995. Fission track evidence for the Neocene rapid uplifting of the eastern Himalayan syntaxis. Chin. Sci. Bull. 40 (16), 1497–1500.
Du, R.H., Wang, L.L., Wang, Y.L., et al., 1985. Formation and development of glacial debris flow in the Guxiang gully, Xizang. In: Lanzhou Institute of Glacier and Permafrost, CAS, Special Issue on China Debris Flow. Science Press, Beijing, pp. 1–18 (In Chinese).
Evans, S.G., Hungr, O., Clague, J.J., 2001. Dynamics of the 1984 rock avalanche and associated distal debris flow on Mount Cayley, British Columbia, Canada: implications for landslide hazard assessment on dissected volcanoes. Eng. Geol. 61, 29–51.
Finnegan, N.J., Hallet, B., Montgomery, D.R., Zeitler, P.K., Stone, J.O., Anders, A.M., Liu, Y.P., 2008. Coupling of rock uplift and river incision in the Nache Barwa-Gyala Peri massif, Tibet. GSA Bull. 120 (1/2), 142–155.
Gansu Regional Geological Survey Team (GRGST), 1995. The 1:200000 Geological Map and Regional Geological Survey Report of Tongmai and Bomi.
Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. Earth Sci. Rev. 162, 227–252.
Ge, Y.G., Cui, P., Su, F.H., 2014. Case history of the disastrous debris flows of Tianmo watershed in Bomi County, Tibet, China: some mitigation muggestions. J. Mount. Sci. 11 (5), 1253–1265.
Geertsema, M., Clague, J.J., Schwab, J.W., Evans, S.G., 2006. An overview of recent large catastrophic landslides in northern British Columbia, Canada. Eng. Geol. 83, 120–143.
Gruber, S., Haeberli, W., 2007. Permafrost in steep bedrock slopes and its temperature related destabilization following climate change. J. Geophys. Res. 112, F02S18. http://dx.doi.org/10.1029/2006JF000547.
Guthrie, R.H., Friele, P., Allstadt, K., Roberts, N., Evans, S.G., Delaney, K.B., Roche, D., Clague, J.J., Jakob, M., 2012. The 6 August 2010 Mount Meager rock slide-debris flow, Coast Mountians, British Columbis: characteristics, dynamics, and implication for hazard and risk assessment. Nat. Hazards Earth Syst. Sci. 12, 1277–1294.
Huggel, C., Clague, J.J., Korup, O., 2012. Is climate change responsible for changing landslide activity in high mountains? Earth Surf. Process. Landforms 37, 77–91.
Hungr, O., Evans, S.G., 2004. Entrainment of debris in rock avalanches: an analysis of a long run-out mechanism. GSA Bull. 116 (9–10), 1240–1252.
IMHE, ITS, 1999. A Study of Typical Mountain Hazards Along Sichuan-Tibet Highway. IMHE (Institute of Mountain Hazards and Environment, the Chinese Academy of Sciences and Water Conservancy Ministry of China) and ITS (Institute of the Traffic Science, the Tibet Autonomous Region). Chengdu Science and Technology University Publishing House, Chengdu, pp. 158–184.
Itakura, Y., Inaba, H., Sawada, T., 2005. A debris-flow monitoring devices and methods bibliography. Nat. Hazards Earth Syst. Sci. 5 (6), 971–977.
Iverson, R., 2012. Elementary theory of bed-sediment entrainment by debris flows and avalanches. J. Geophys. Res. 117, F03006–F03022.
Iverson, R., LaHusen, R., Major, J., Zimmerman, C., 1994. Debris flow against obstacles an dbends: dynamics and deposits. EOS Trans. Am. Geopgys. Union 75, 274.
Iverson, R., Reid, M., Lahusen, R., 1997. Debris-flow mobilization from landslides. Annu. Rev. Earth Planet. Sci. 25, 85–138.
Jibson, R.W., Harp, E.L., Schulz, W., Keefer, D.K., 2006. Large rock avalanches triggered by the M7.9 Denali Fault, Alaska, earthquake of 3 November 2002. Eng. Geol. 83, 144–160.
Johnson, A.M., Rodine, J.R., 1984. Debris flow. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. John Wiley & Sons, Chichester, UK, pp. 257–361.
King, G., Herman, F., Guralnik, B., 2016. Northward migration of the eastern Himalayan syntaxis revealed by OSL thermochronometry. Science 353 (6301), 800–804.
Korup, O., Clague, J.J., 2009. Natural hazards, extreme events, and mountain topography. Quat. Sci. Rev. 28, 977–990.
Li, D.J., You, Y., 1992. Bursting of the Midui moraine lake in Bomi, Xizang. Mountain Res. 10 (4), 219–224 (In Chinese).
Li, J.J., Zheng, B.X., Yang, X.J., 1986. Tibet Glacier. 1-36. Science Press, Beijing, pp. 217–228 (In Chinese).
Liu, N., Zhang, J., Lin, W., Cheng, W., Chen, Z., 2009. Draining Tangjiashan barrier lake after Wenchuan earthquake and the flood propagation after the dam break. Sci. Chin. E 52 (4), 801–809 (In Chinese).
Lü, R.R., Li, D.J., 1989. Debris flow induced by melted water of Dongrunongbu, Bomi, Tibet. Glacies Frozen Earth 11 (2), 148–160 (In Chinese).
Lu, A.X., Deng, X.F., Zhao, S.X., Wang, L.H., Zhang, Y.S., 2006. Cause of debris flow in Guxiang valley in Bomi, Tibet autonomous region, 2005. J. Glaciol. Geocryol. 28 (6), 956–960 (In Chinese).
Mi, D.S., Xie, Z.C., Feng, Q.H., 2002. Glacier Inventory of China, XI, the Ganga Drainage Basin. Xi′an Cartographic Press, Xi′an, pp. 9–437 (In Chinese).
Prochaska, A.B., Santi, P.M., Higgins, J.D., Cannon, S.H., 2008. A study of methods to estimate debris flow velocity. Landslides 5, 431–444. http://dx.doi.org/10.1007/s10346-008-0137-0.
Ren, J.W., Shen, J., Cao, Z.Q., Wang, Y.P., 2000. Quaternary faulting of Jiali fault, southeastern Tibetan plateau. Seismol. Geol. 22 (4), 344–350 (In Chinese).
Ren, J.W., Shan, X.J., Shen, J., Gesang, Zhasang, Deng, G.Y., Zhang, J., 2001. Geological characteristics and kinematics of the rock fall-landslide in Yigong, Southeastern Tibet. Geol. Rev. 47 (6), 642–648 (In Chinese).
Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65 (66), 31–47.

Rickenmann, D., 1999. Empirical relationships for debris flow. Nat. Hazards 19, 47–77.
Scheidl, C., McArdell, B., Ricknmann, D., 2015. Debris-flow velocities and superelevation in a curved laboratory channel. Can. Geotech. J. 52, 305–317.
Shang, Y.J., Yang, Z.F., Li, L.H., Liu, D.A., Liao, Q.L., Wang, Y.C., 2003. A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin. Geomorphology 54, 225–243.
Shang, Y.J., Park, H., Yang, Z.F., Yang, J., 2005. Distribution of landslides adjacent to the northern side of the Yarlu Tsangpo Grand Canyon in Tibet, China. Environ. Geol. 48, 721–741.
Shi, Y.F., Yang, Z.H., Xie, Z.C., Du, R.H., 1964. The glacial debris flow in Guxiang, Tibet. Chin. Sci. Bull. 6, 542–544.
Takahashi, T., 2014. Debris flow mechanics, prediction and countermeasures, 2nd edition. 103–168. Taylor & Francis, London, pp. 259–334.
Tang, C., Rengers, N., Van Asch, Th.W.J., Yang, Y.H., Wang, G.F., 2011. Triggering conditions and depostional characteristics of a disastrous debris flow event in Zhouqu city, Gansu Province, northwester China. Nat. Hazards Earth Syst. Sci. 11, 2903–2912.
Wasowski, J., Bovenga, F., 2014. Investigating landslides and unstable slopes with satellite multi-temporal interferometry: current issues and future perspectives. Eng. Geol. 2014 (174), 103–138.
Wu, J.S., Kang, Z.C., Tian, L.Q., 1990. Study on Observation of Jiangjiagou Debris Flow in Yunnan Province. Science Press, Beijing, pp. 27–46.
Wu, J.S., Cheng, Z.L., Geng, X.Y., 2005. Formation of dam from debris flow in the Southeast Tibet. J. Mount. Sci. 23 (4), 399–405 (In Chinese).
Yang, Z.H., 1991. Summary of Super Debris Flow of Peilong Valley in Sichuan-Tibet Highway. Proceedings of Second Conference about Debris Flow. Science Press, Beijing, pp. 252–254.
Yang, W., Yao, T.D., Xu, B., Ma, L., Wang, Z., Wan, M., 2008. Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo mountains, southeast Tibetan Plateau. Chin. Sci. Bull. 53, 2547–2551.
Yang, W., Guo, X., Yao, T., Zhu, M., Wang, Y., 2016. Recent accelerating mass loss of southeast Tibetan glaciers and the relationship with changes in macroscale atmospheric circulations. Clim. Dyn. 47, 805–815.
Zeitler, P.K., Meltzer, A.S., Brown, L., 2014. Tectonics and topographic evolution of Namche Barwa and the easternmost Lhasa block, Tibet. GSA Bull. Spec. 507, 23–58.
Zeng, Q.L., 2007a. Formation of Huge-Thick Loose Accumulations in Southeast Tibet with Associated Hazards Modes and Mitigations: A Case Study in Ranwu to Lulang Section of Sichuan-Tibet Highway. Thesis of University of Chinese Academy of Science, pp. 2007.
Zeng, Q.L., Yang, Z.F., Zhang, X.J., Shang, Y.J., Zhang, L.Q., 2007b. Hazard model and countermeasure to super-large debris flow in Parlung River, case study of the section from Zamu town to Guxiang gully. J. Geol. Hazard Control 18 (2), 27–33 (In Chinese).
Zhang, J.S., Xie, H., Wang, X.D., Fan, J.H., 2015. Debris-flow of Jianmupuqu ravine in Tibet. J. Catastrophol. 30 (3), 99–103 (In Chinese).
Zhou, C.C., 2007. Large Debris Flow Took Place in Songrao Village, Bomi county, Xizang. http://www.ls.xzgtt.gov.cn/xwdt/201008/t20100818_741916.htm.
Zhu, P.Y., Cheng, Z.L., You, Y., 2000. Research on causes of river blocking by sediment delivery of Peilonggou gully debris flow in the Sichuan-Xizang highway. Chin. J. Nat. Disasters 9 (1), 80–83.